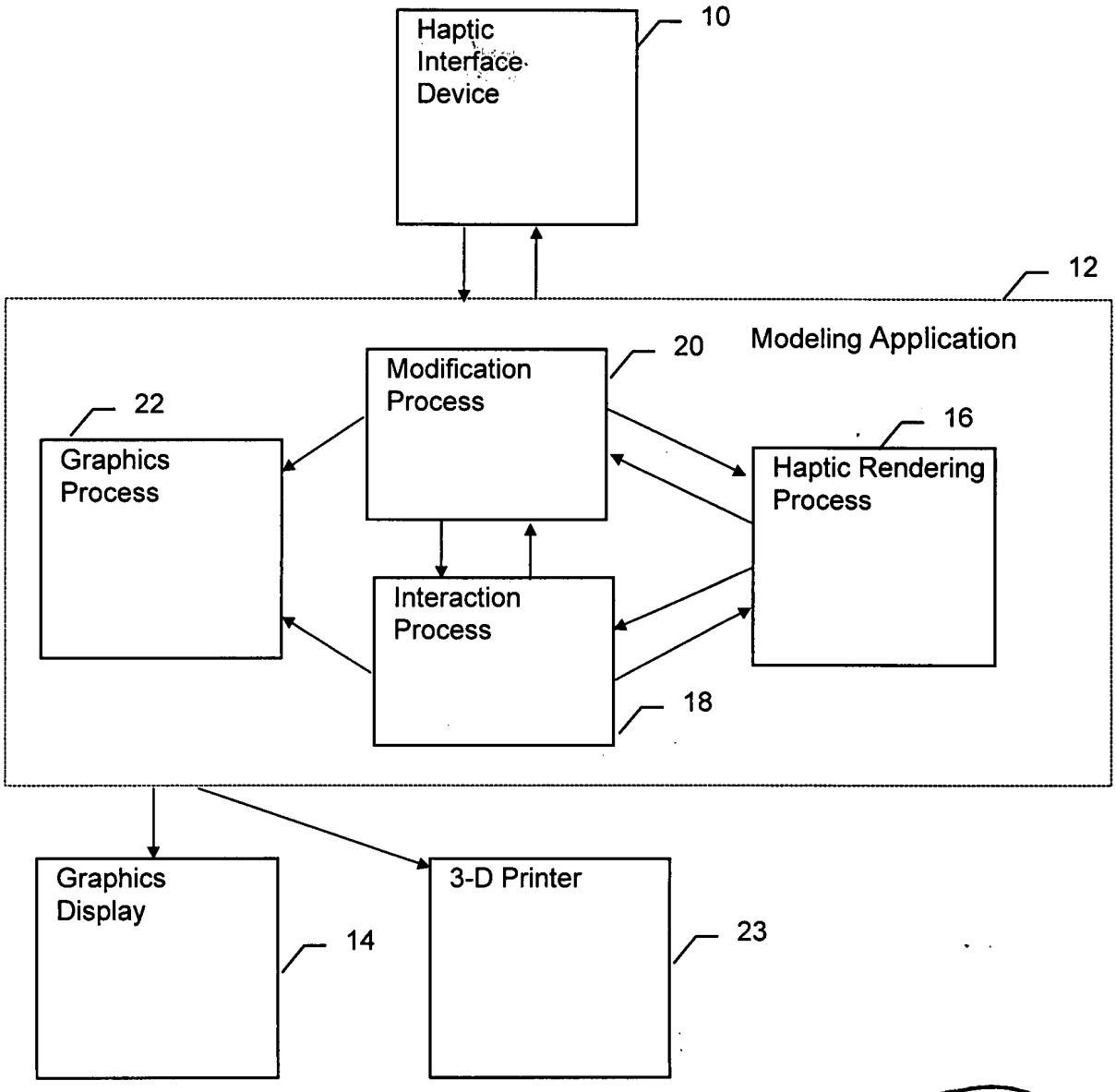
Haptic Interface Device
10
12
Modeling Application
Modification Process
20
22
16
Graphics Process
Haptic Rendering Process
Interaction Process
18
Graphics Display
14
3-D Printer
23

Fig. 1

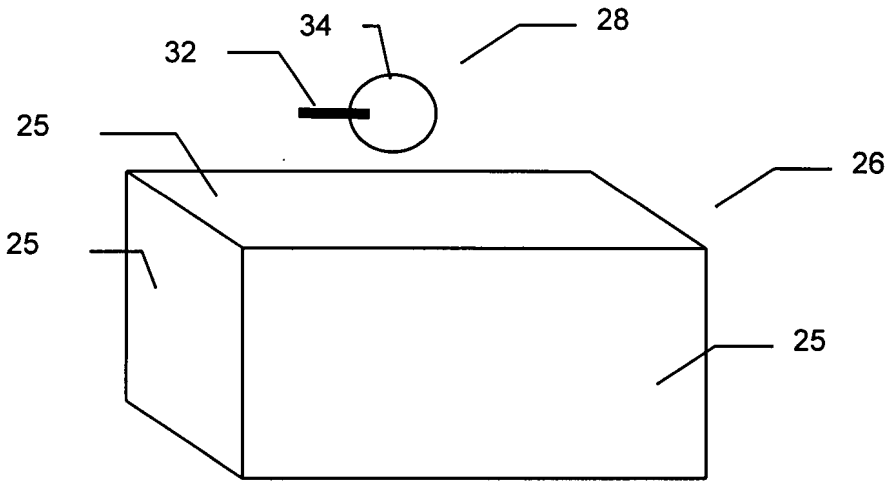

FIG. 2A

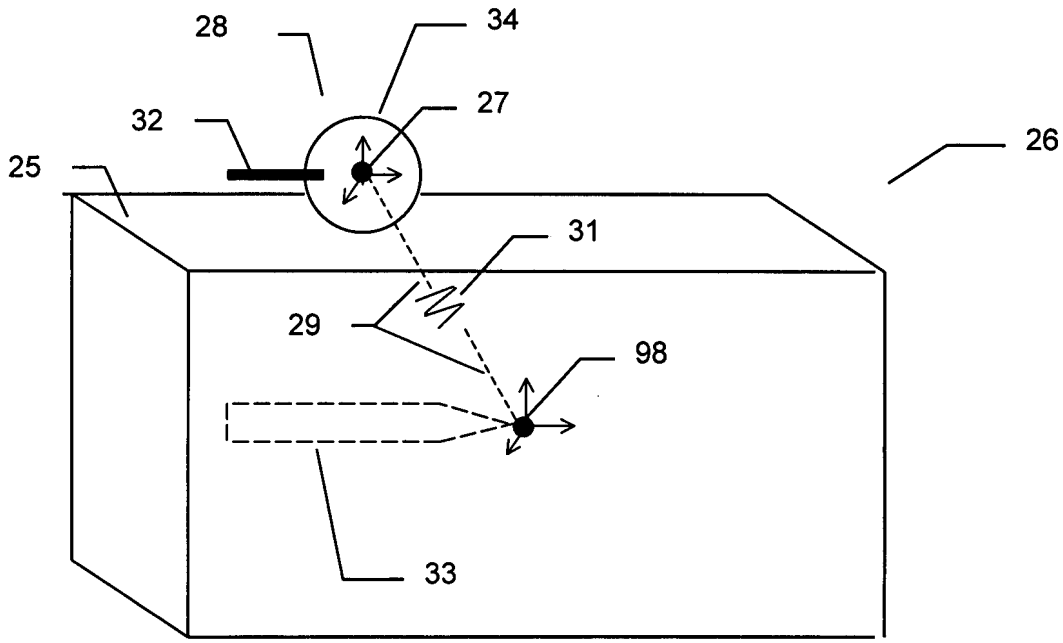

FIG. 2B

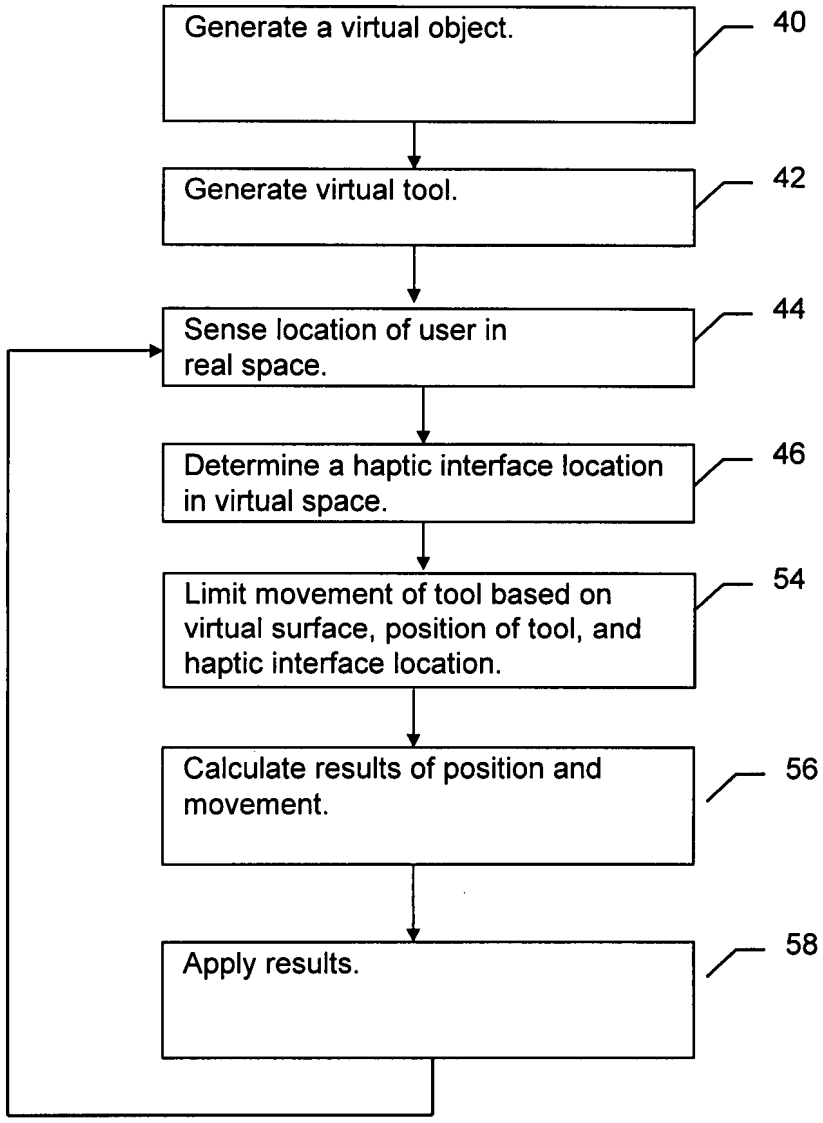
Generate a virtual object.
40
Generate virtual tool.
42
Sense location of user in real space.
44
Determine a haptic interface location in virtual space.
46
Limit movement of tool based on virtual surface, position of tool, and haptic interface location.
54
Calculate results of position and movement.
56
Apply results.
58

Fig. 3

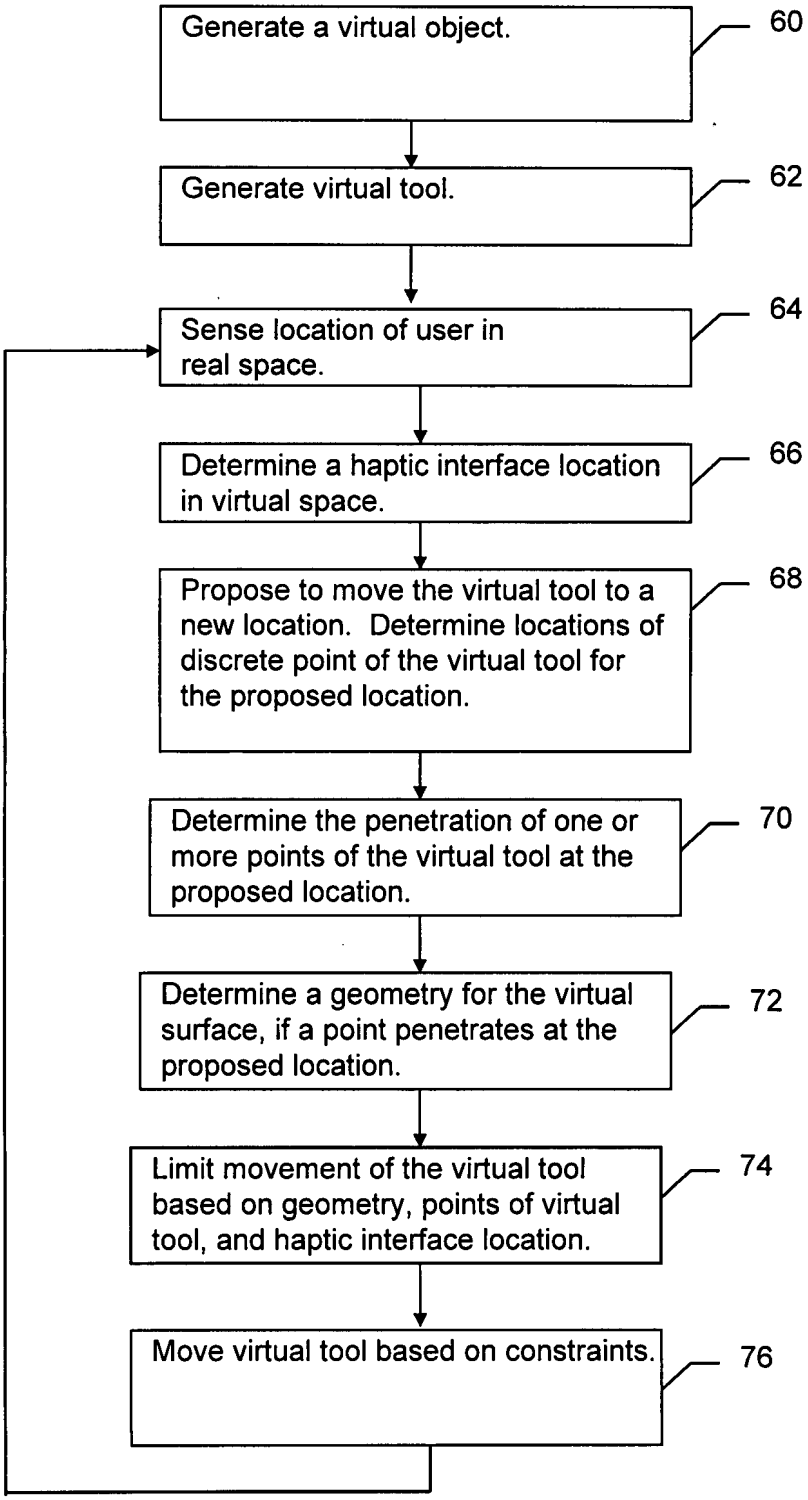
Generate a virtual object.
60
Generate virtual tool.
62
Sense location of user in real space.
64
Determine a haptic interface location in virtual space.
66
Propose to move the virtual tool to a new location. Determine locations of discrete point of the virtual tool for the proposed location.
68
Determine the penetration of one or more points of the virtual tool at the proposed location.
70
Determine a geometry for the virtual surface, if a point penetrates at the proposed location.
72
Limit movement of the virtual tool based on geometry, points of virtual tool, and haptic interface location.
74
Move virtual tool based on constraints.
76

Fig. 4

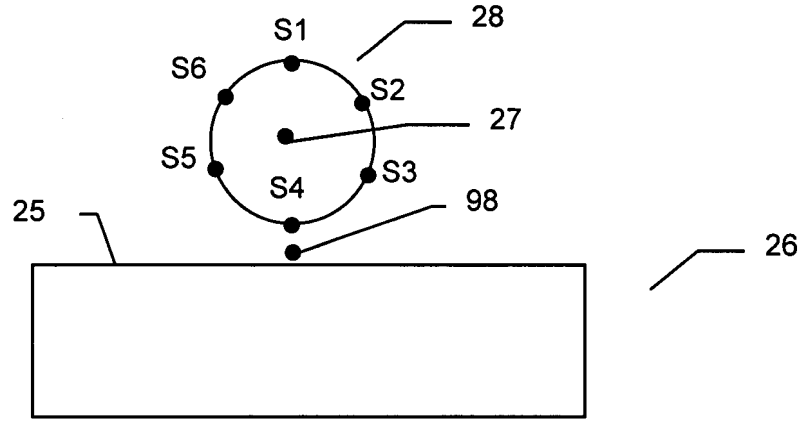

FIG. 5A

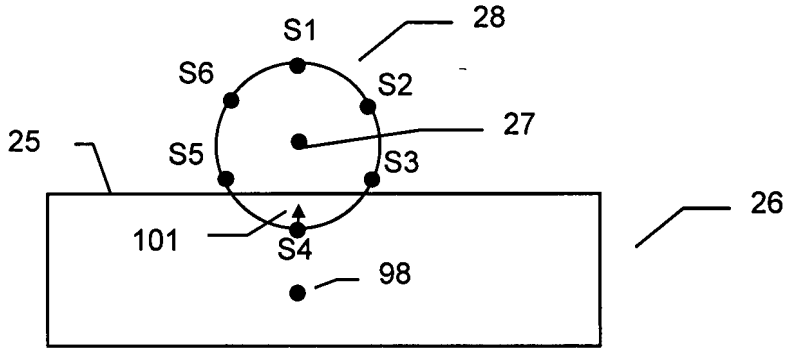

FIG. 5B

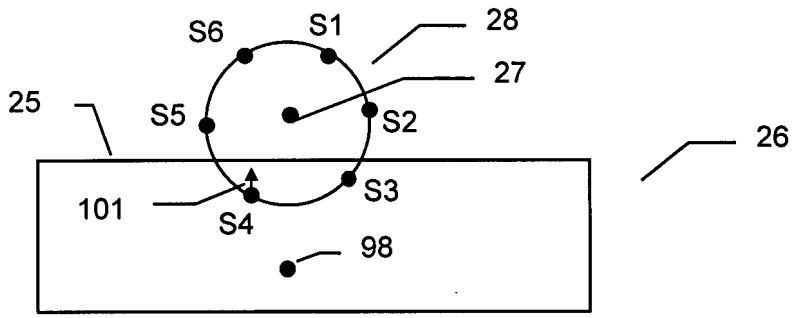

FIG. 5C

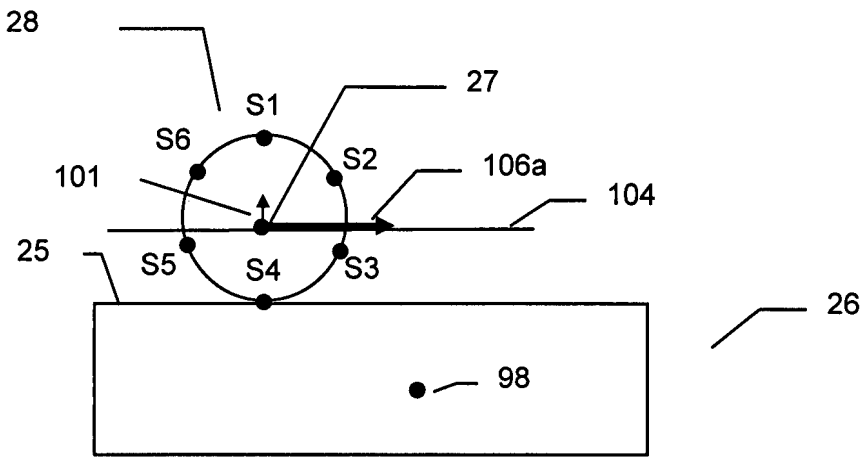

FIG. 5D

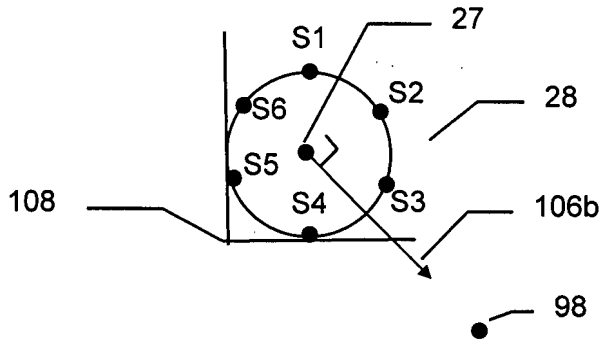

FIG. 5E

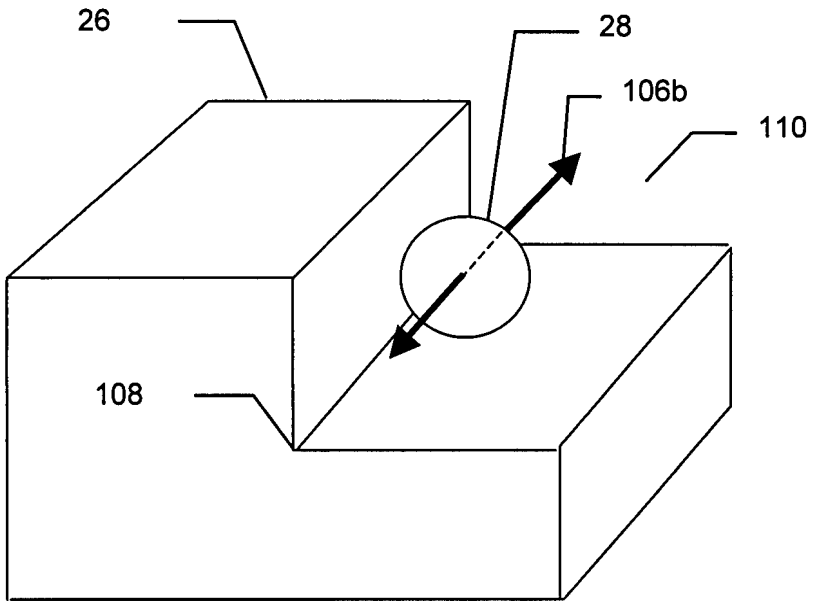

FIG. 5F

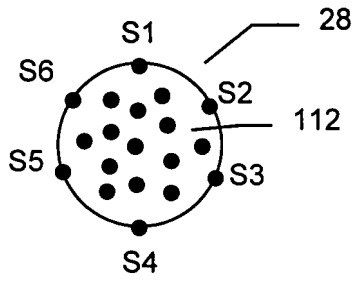

FIG. 6

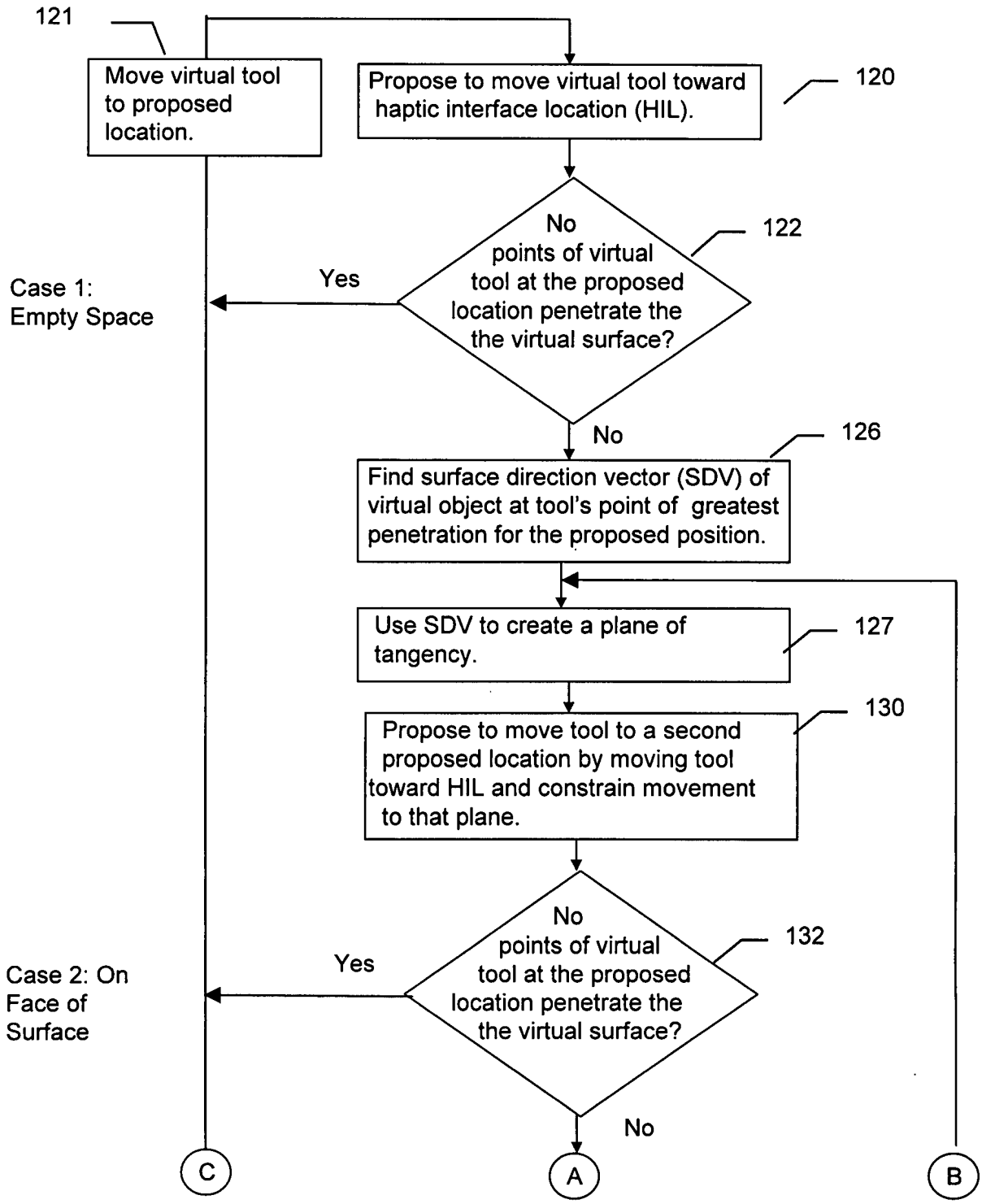
121
Move virtual tool to proposed location.
Propose to move virtual tool toward haptic interface location (HIL).
120
No points of virtual tool at the proposed location penetrate the the virtual surface?
122
Yes
Case 1: Empty Space
No
126
Find surface direction vector (SDV) of virtual object at tool's point of greatest penetration for the proposed position.
Use SDV to create a plane of tangency.
127
Propose to move tool to a second proposed location by moving tool toward HIL and constrain movement to that plane.
130
No points of virtual tool at the proposed location penetrate the the virtual surface?
132
Yes
Case 2: On Face of Surface
No
C
A
B

Fig. 7A

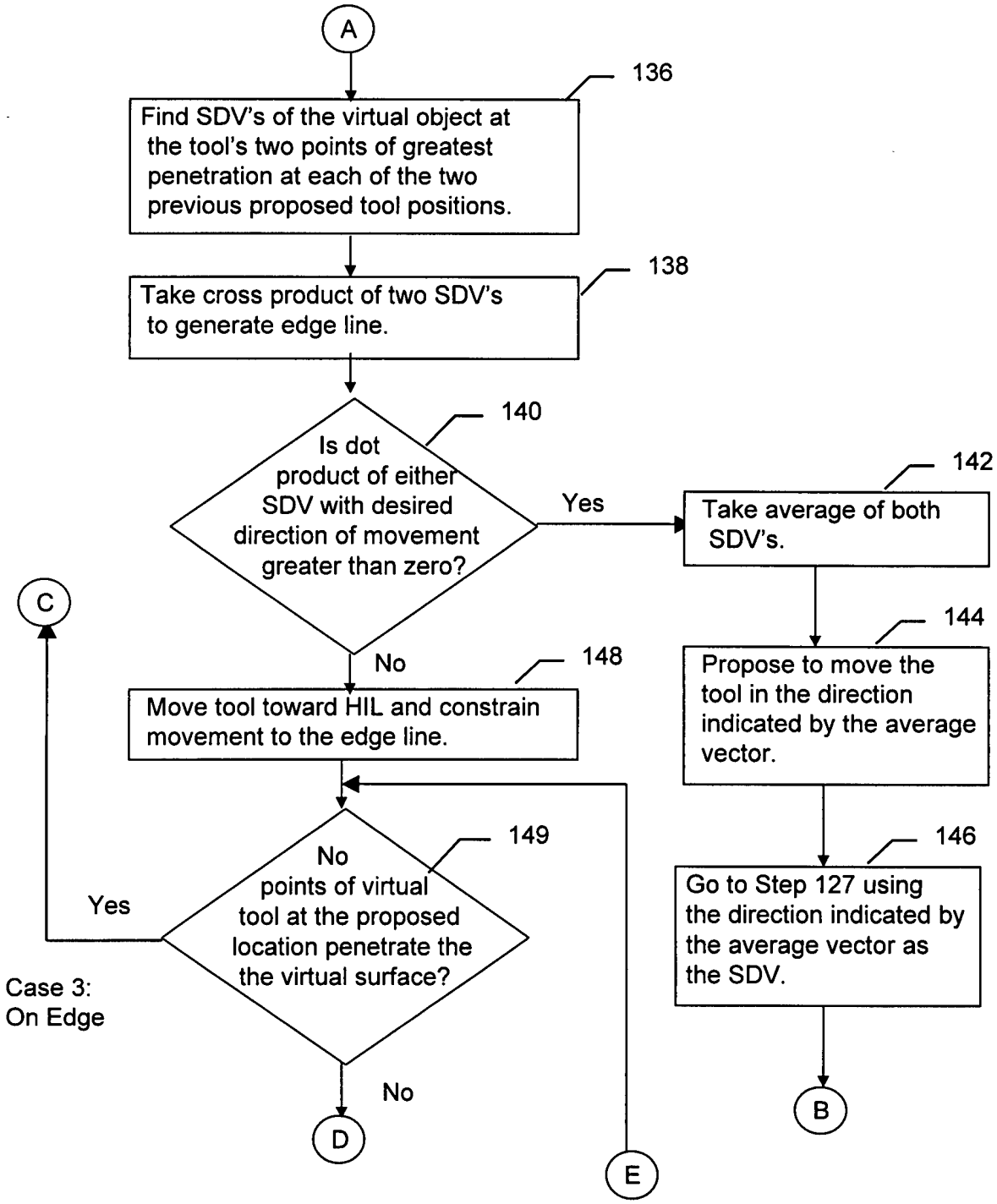
A
136
Find SDV's of the virtual object at the tool's two points of greatest penetration at each of the two previous proposed tool positions.
138
Take cross product of two SDV's to generate edge line.
140
Is dot product of either SDV with desired direction of movement greater than zero?
Yes
142
Take average of both SDV's.
144
Propose to move the tool in the direction indicated by the average vector.
146
Go to Step 127 using the direction indicated by the average vector as the SDV.
B
No
148
Move tool toward HIL and constrain movement to the edge line.
149
No points of virtual tool at the proposed location penetrate the the virtual surface?
Yes
C
Case 3:
On Edge
No
D
E

Fig. 7B

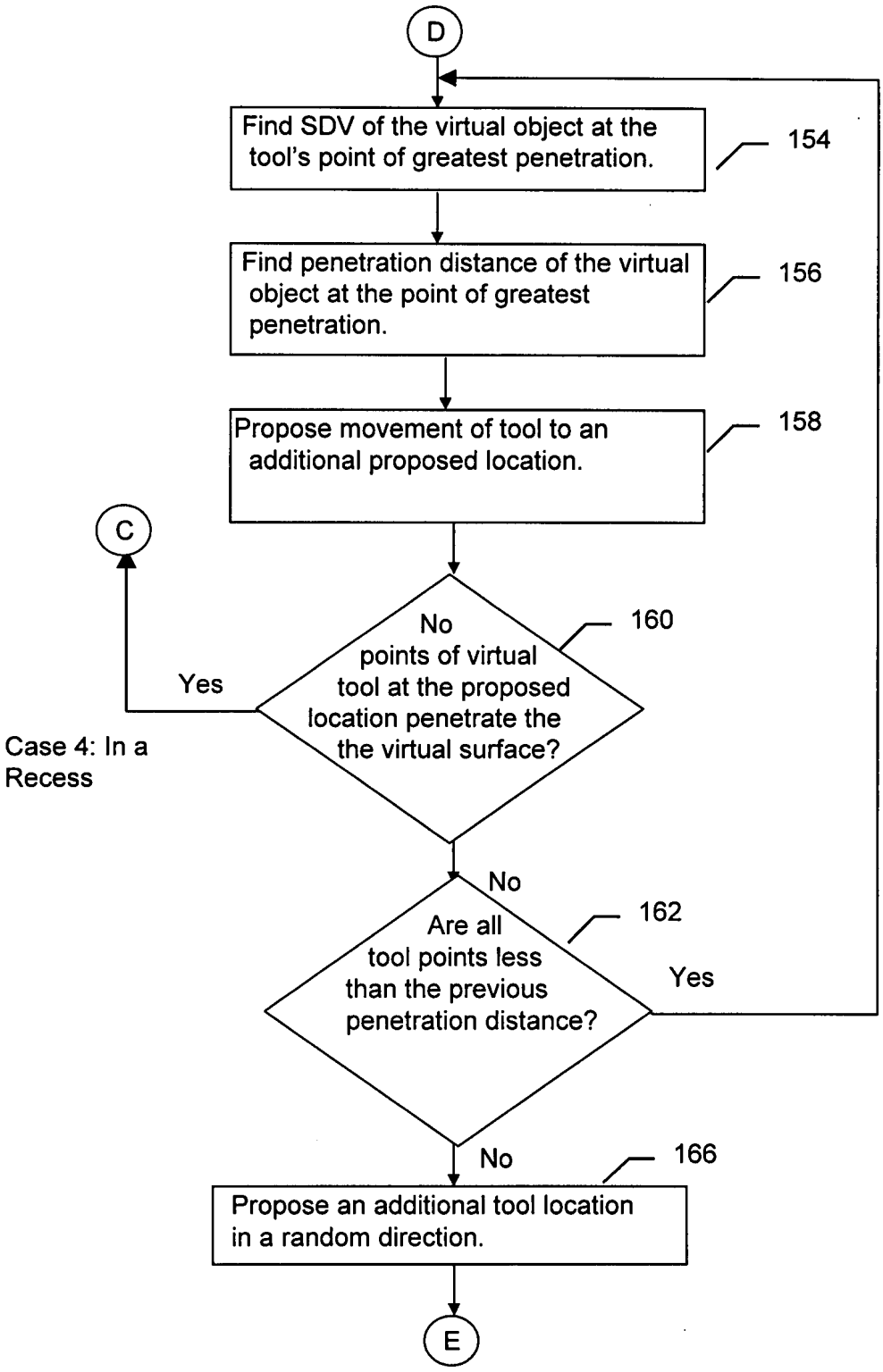
D
Find SDV of the virtual object at the tool's point of greatest penetration.
154
Find penetration distance of the virtual object at the point of greatest penetration.
156
Propose movement of tool to an additional proposed location.
158
C
No
points of virtual tool at the proposed location penetrate the the virtual surface?
160
Yes
Case 4: In a Recess
No
Are all tool points less than the previous penetration distance?
162
Yes
No
166
Propose an additional tool location in a random direction.
E

FIG. 7C

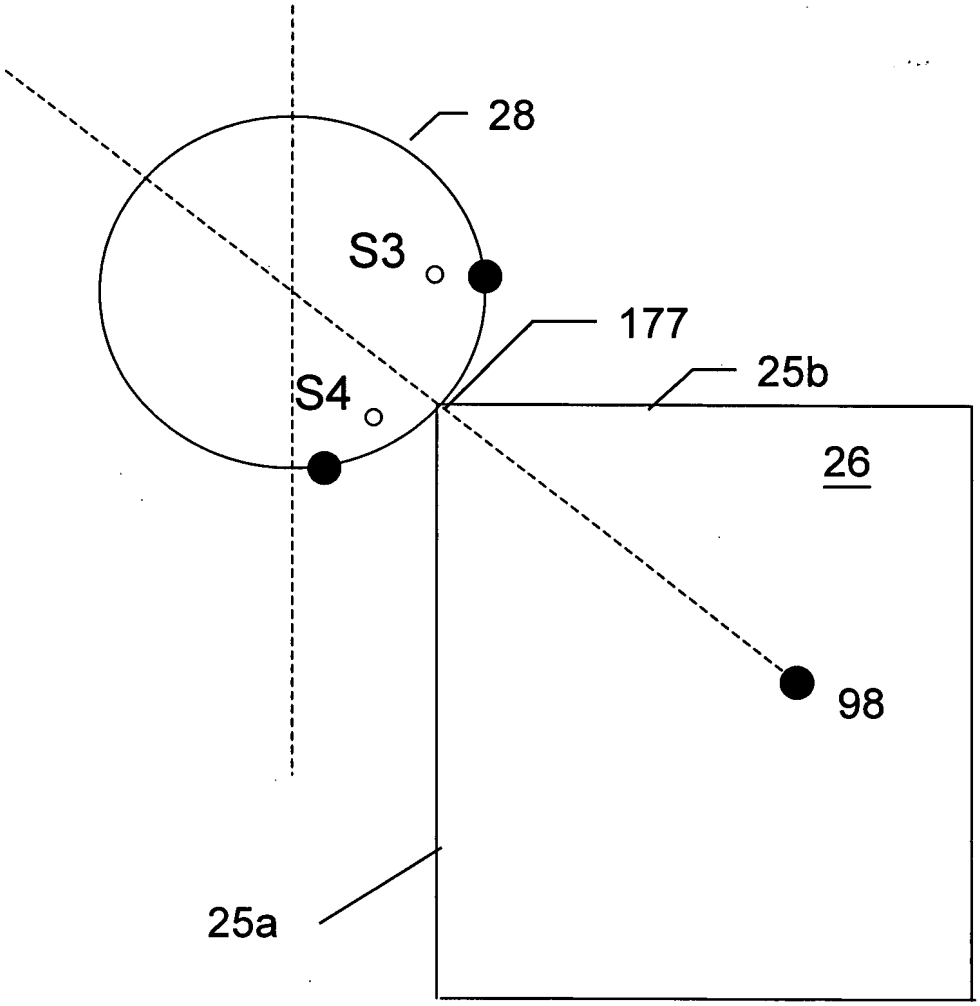

FIG. 8A

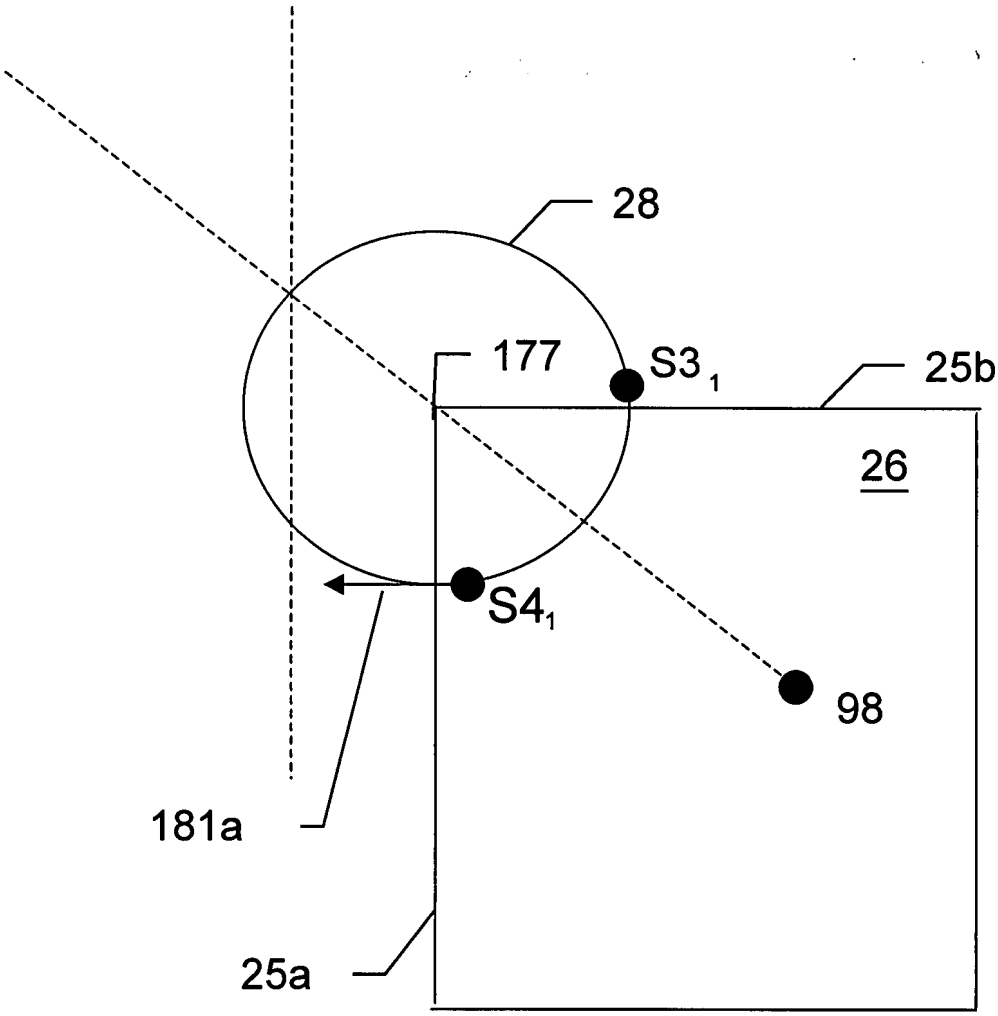

FIG. 8B

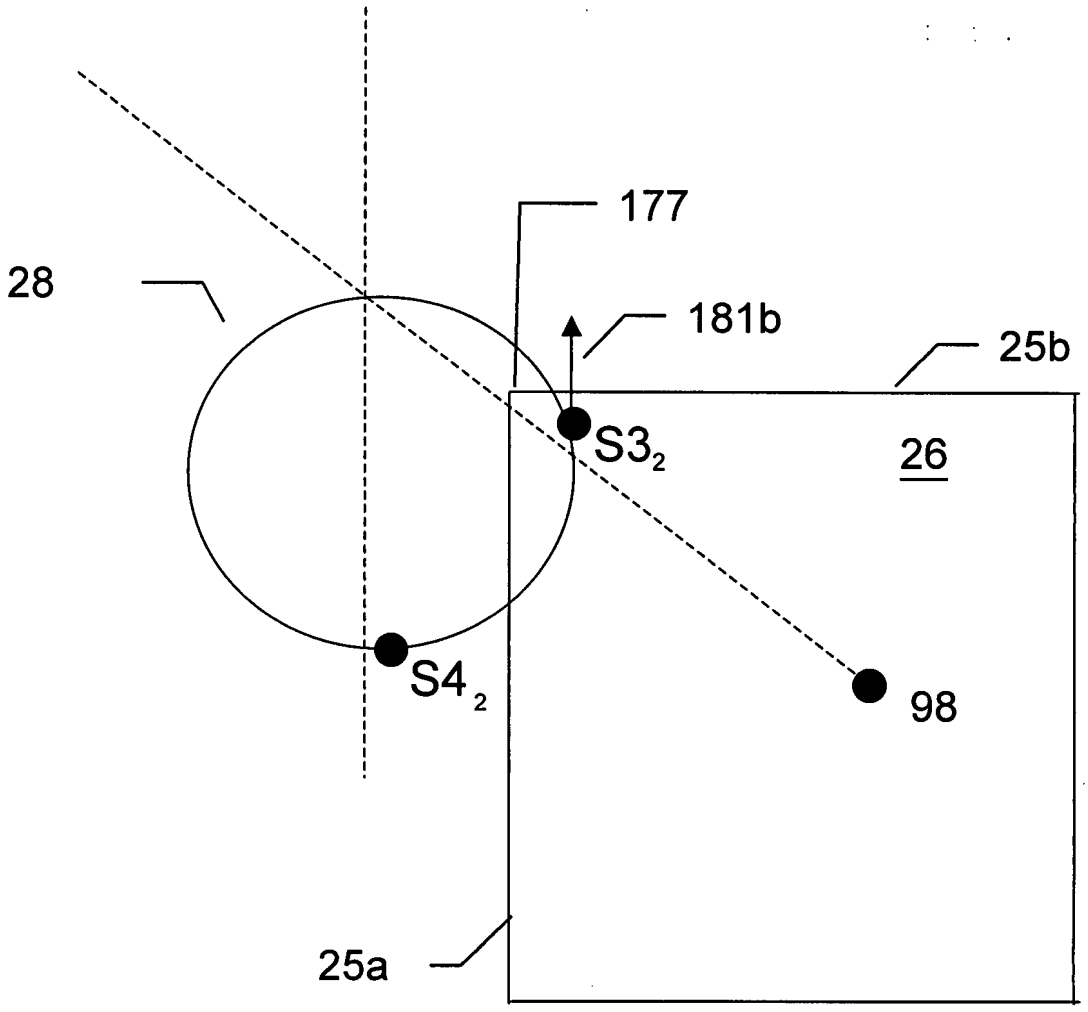

FIG. 8C

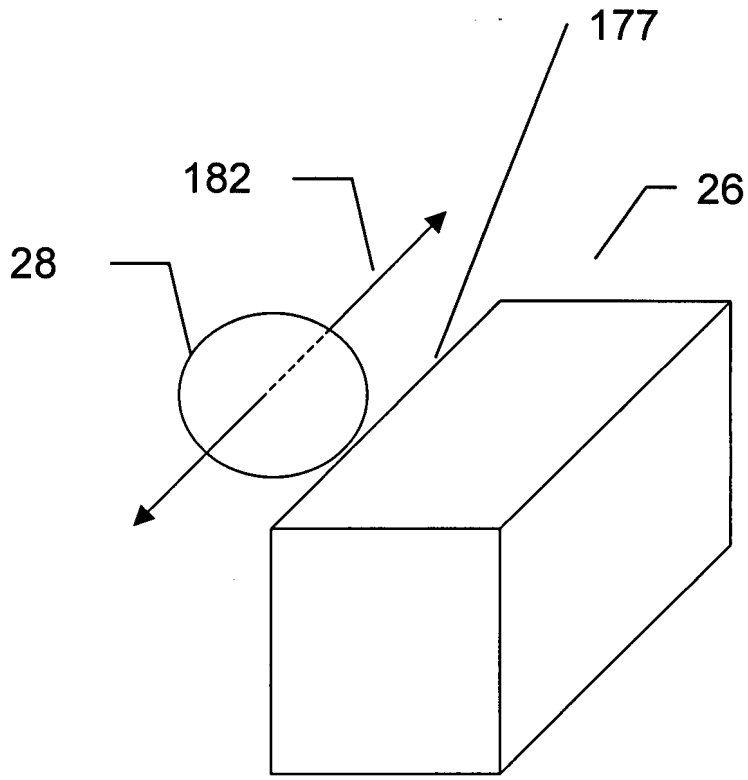

FIG. 8D

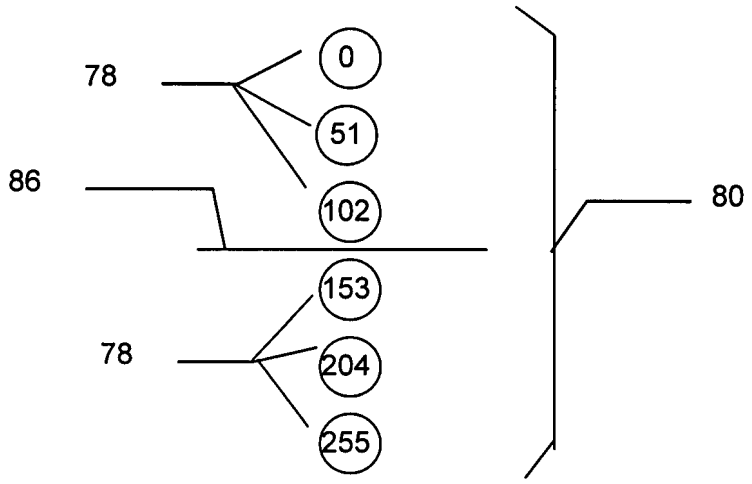

FIG. 9

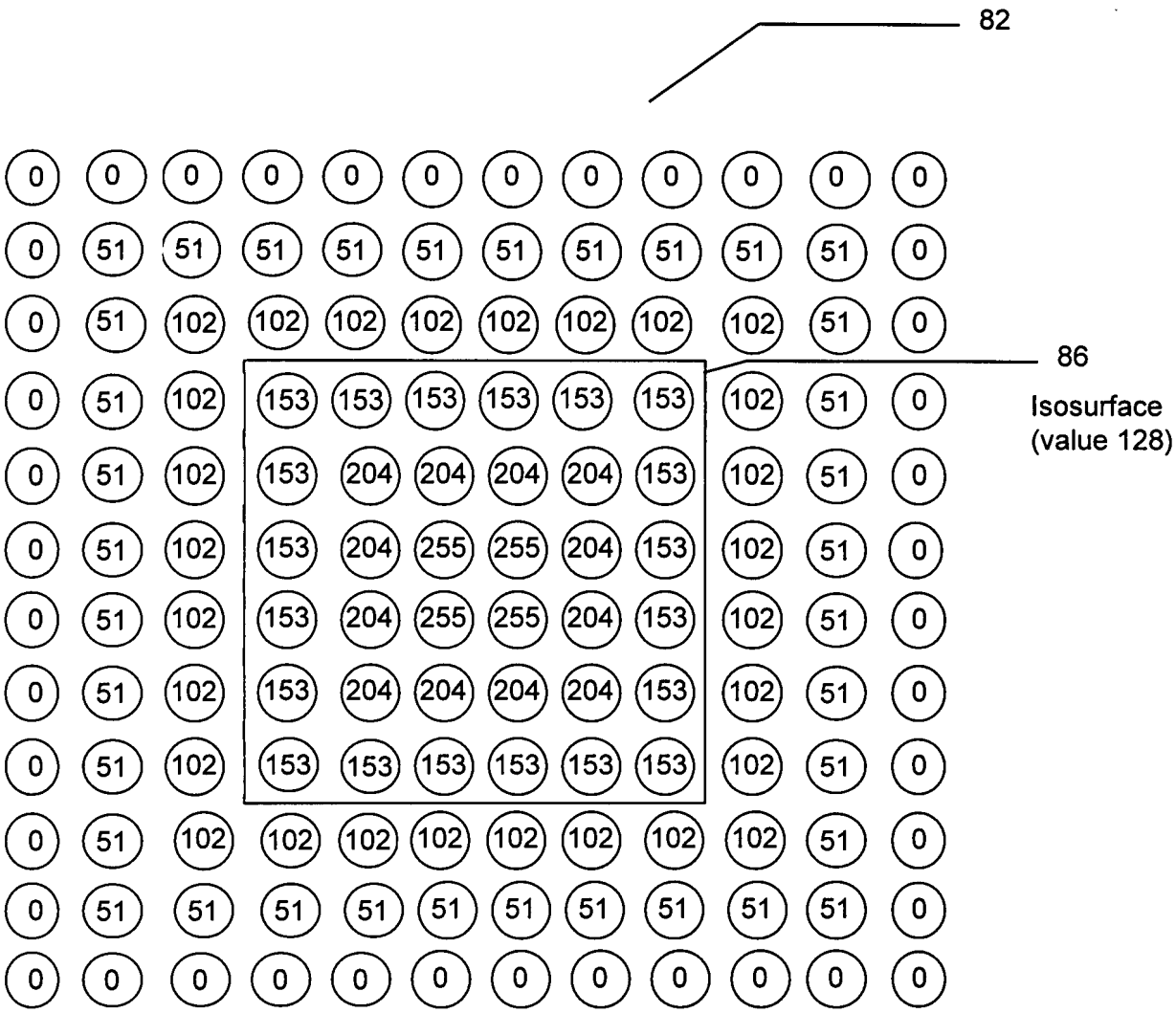
82
86
Isosurface
(value 128)
0 0 0 0 0 0 0 0 0 0 0 0
0 51 51 51 51 51 51 51 51 51 51 0
0 51 102 102 102 102 102 102 102 102 51 0
0 51 102 153 153 153 153 153 153 102 51 0
0 51 102 153 204 204 204 204 153 102 51 0
0 51 102 153 204 255 255 204 153 102 51 0
0 51 102 153 204 255 255 204 153 102 51 0
0 51 102 153 204 204 204 204 153 102 51 0
0 51 102 153 153 153 153 153 153 102 51 0
0 51 102 102 102 102 102 102 102 102 51 0
0 51 51 51 51 51 51 51 51 51 51 0
0 0 0 0 0 0 0 0 0 0 0 0

Fig. 10

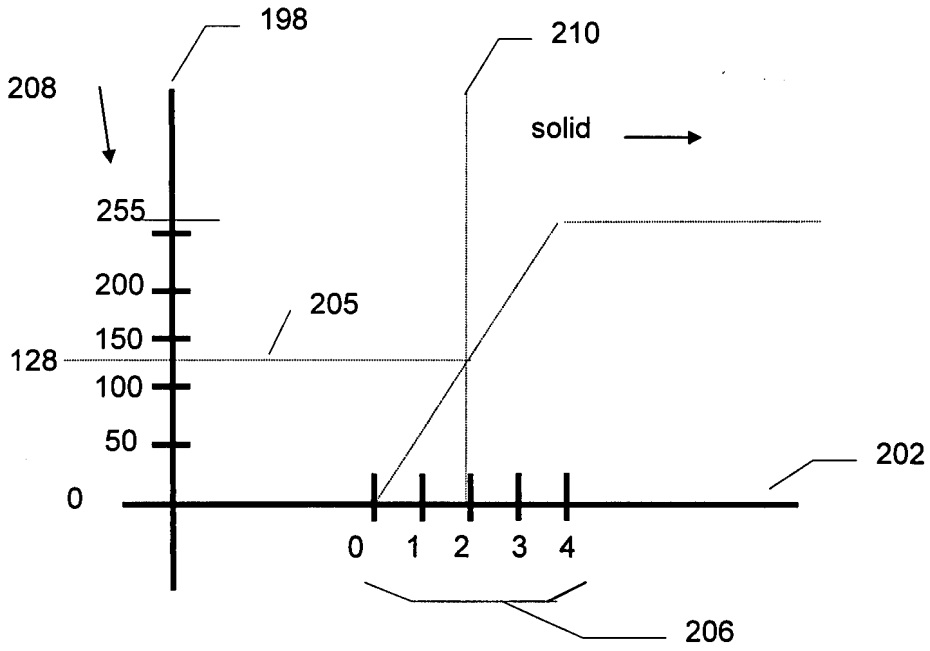

Fig. 11

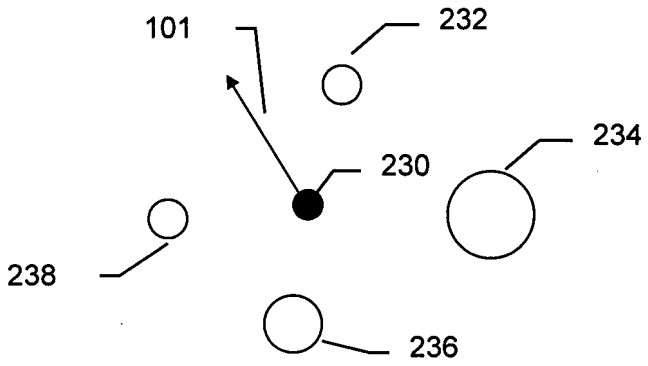

FIG. 12

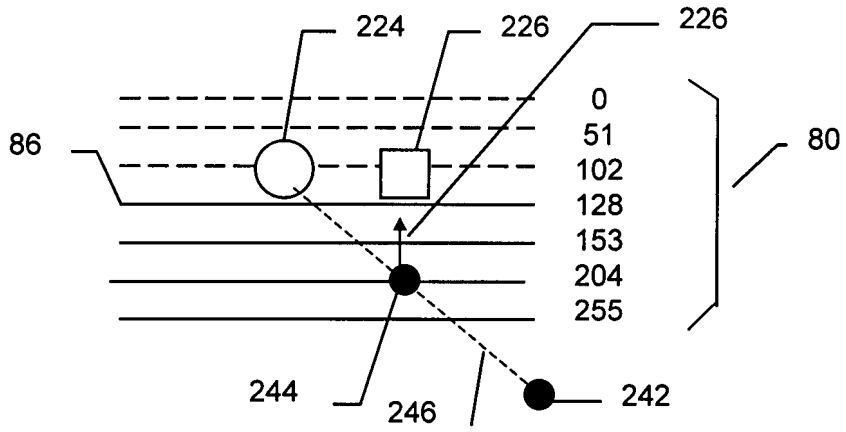

Fig. 13

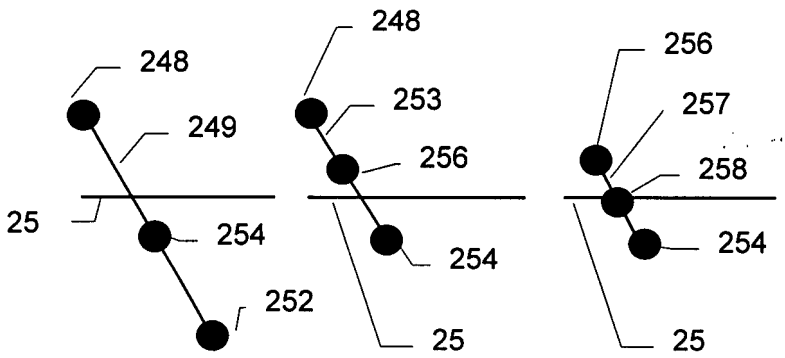

FIG. 14A FIG. 14B FIG. 14C

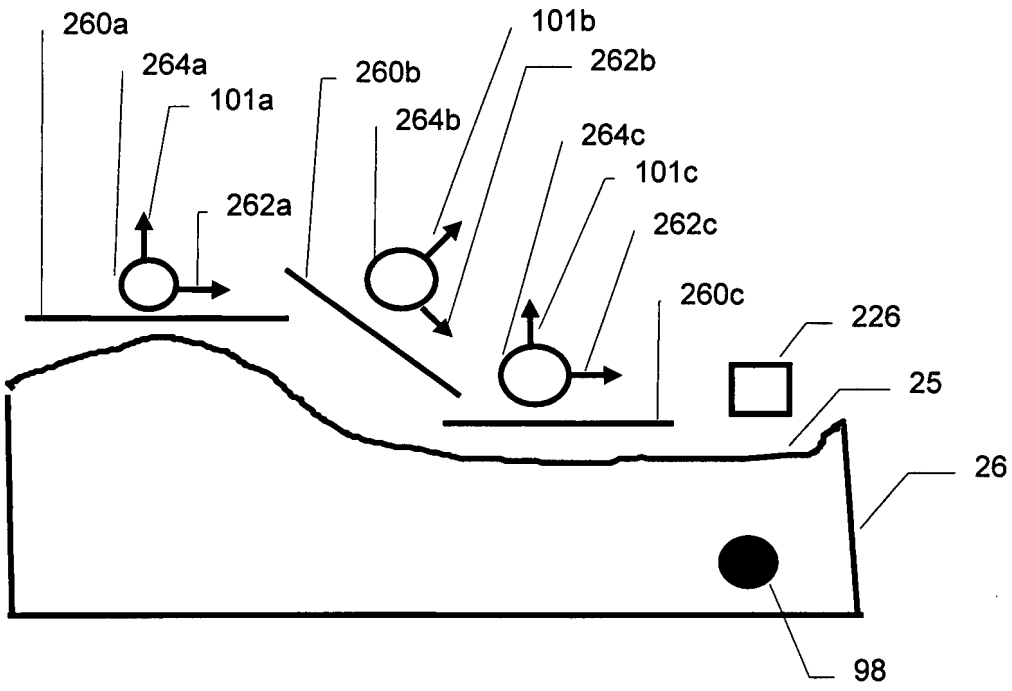

FIG. 15

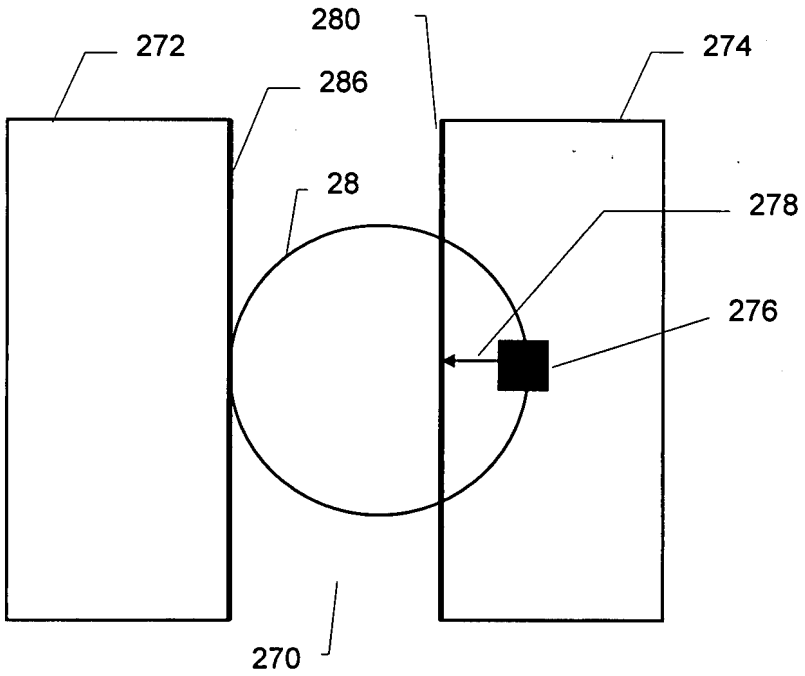

FIG. 16A

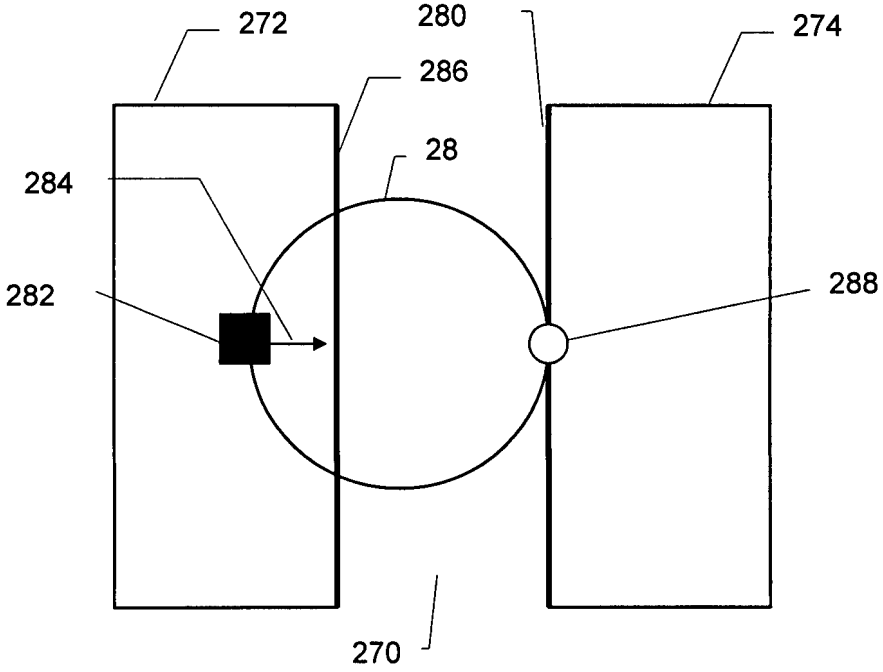

FIG. 16B

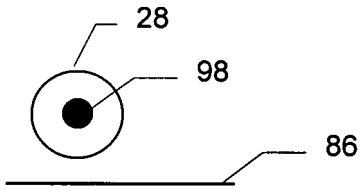

FIG. 17A

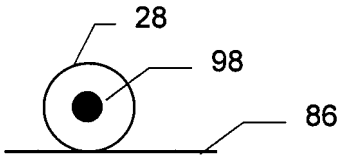

FIG. 17B

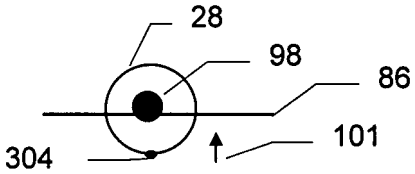

FIG. 17C

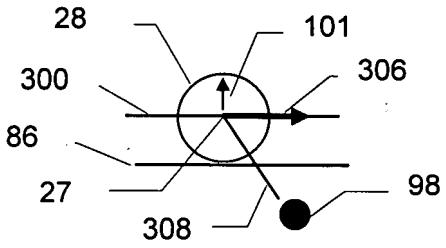

FIG. 17D

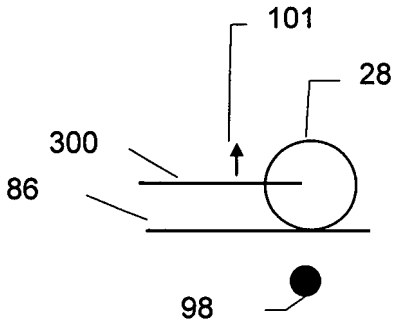

FIG. 17E

345/419

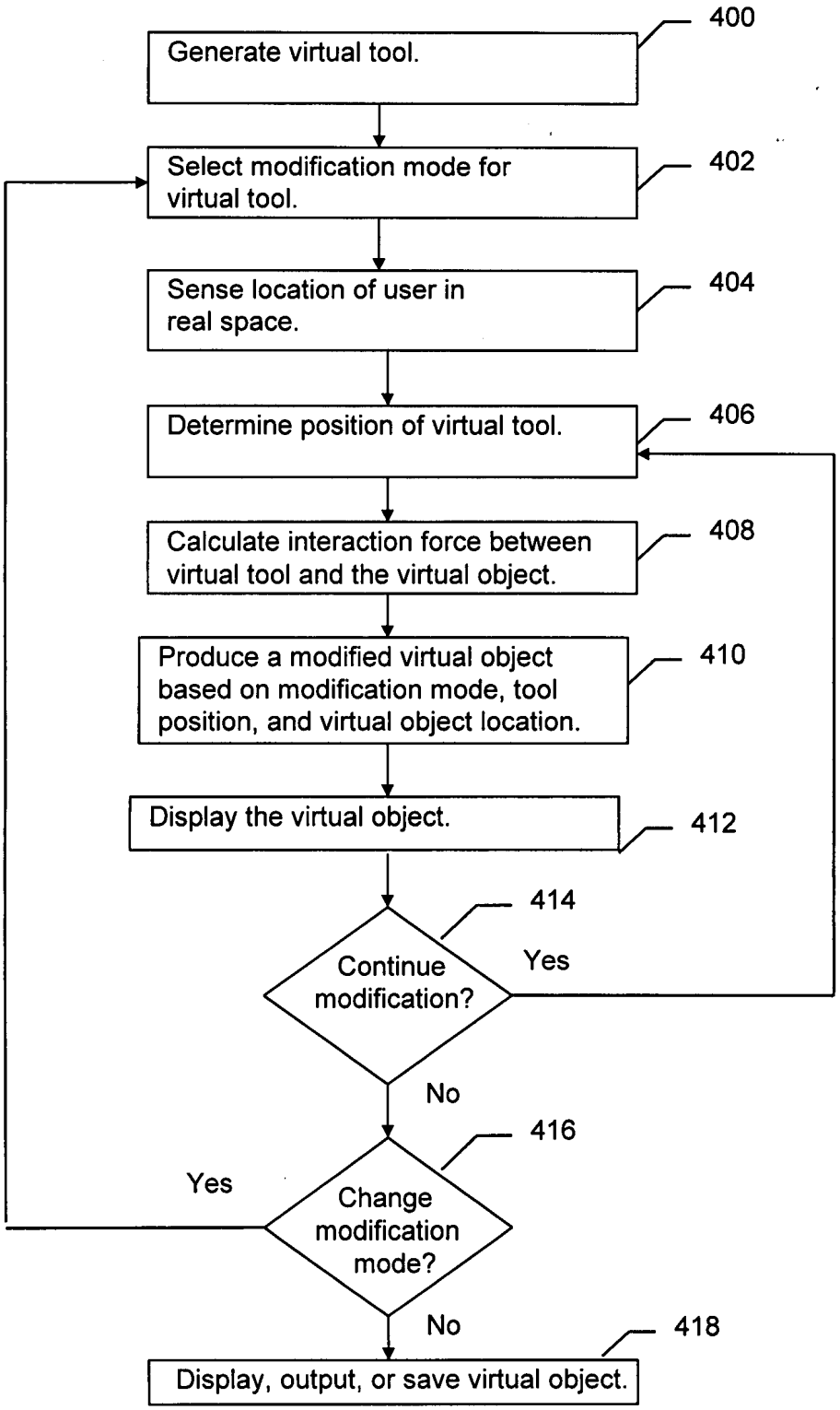

Fig. 18

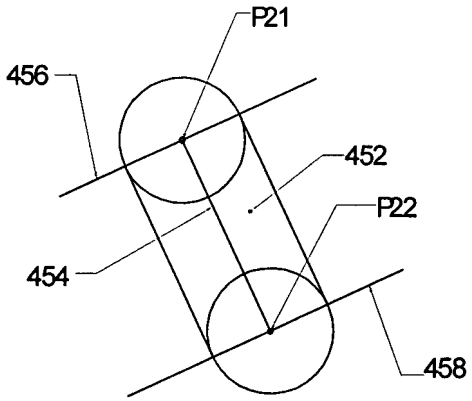

FIG. 19A

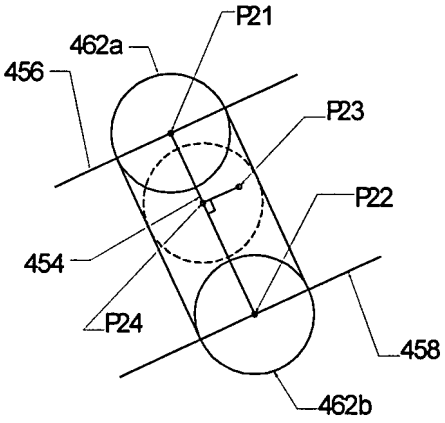

FIG. 19B

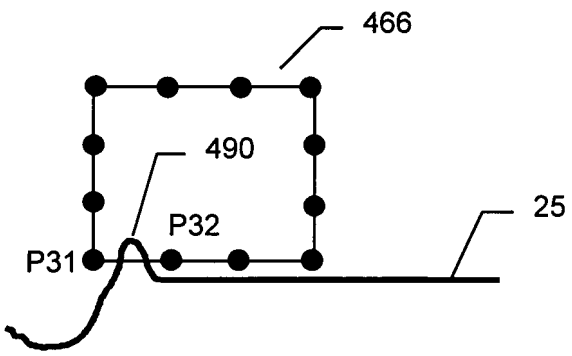

FIG. 20

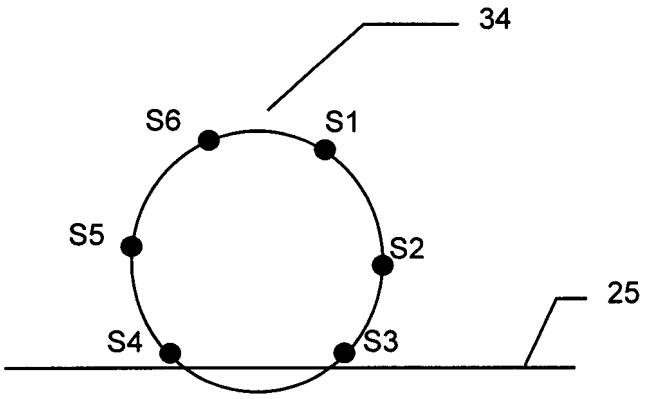

FIG. 21

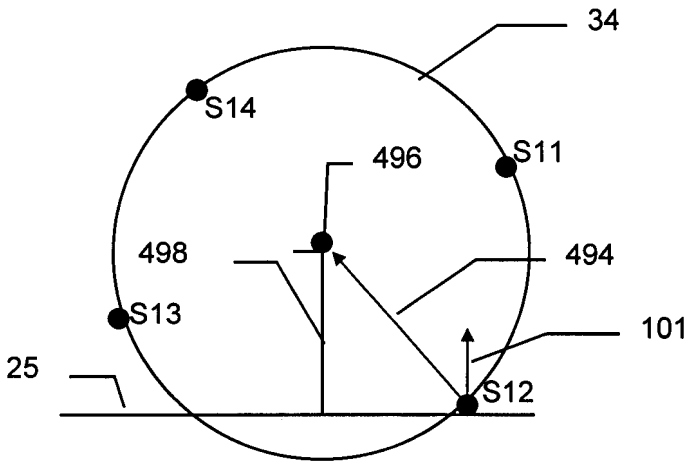

FIG. 22

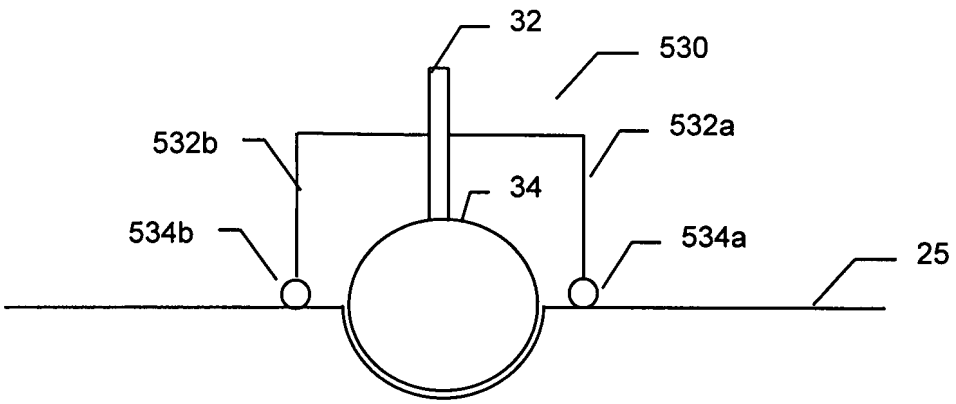

FIG. 23A

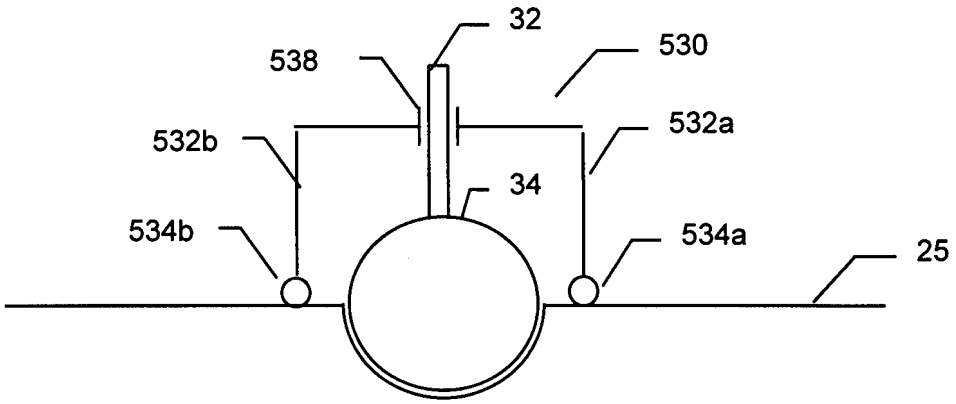

FIG. 23B

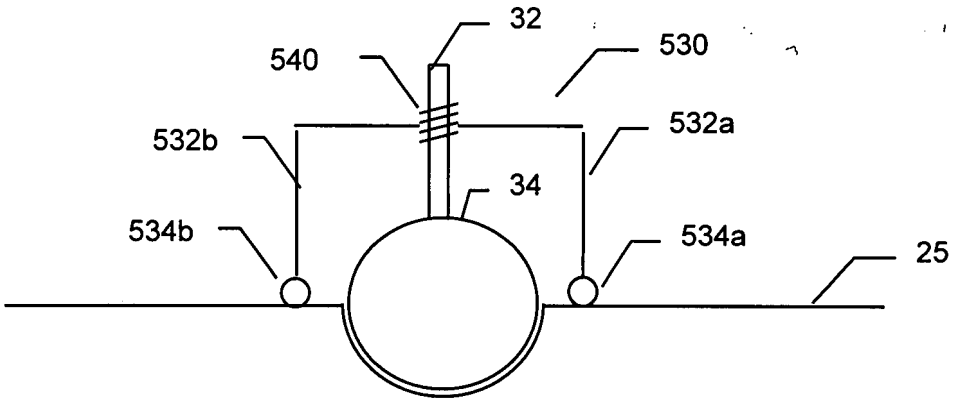

FIG. 23C

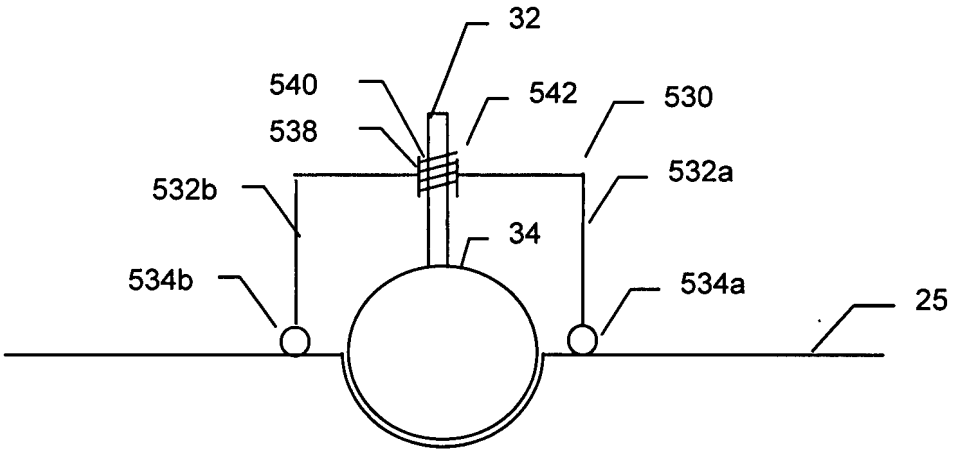

FIG. 23D

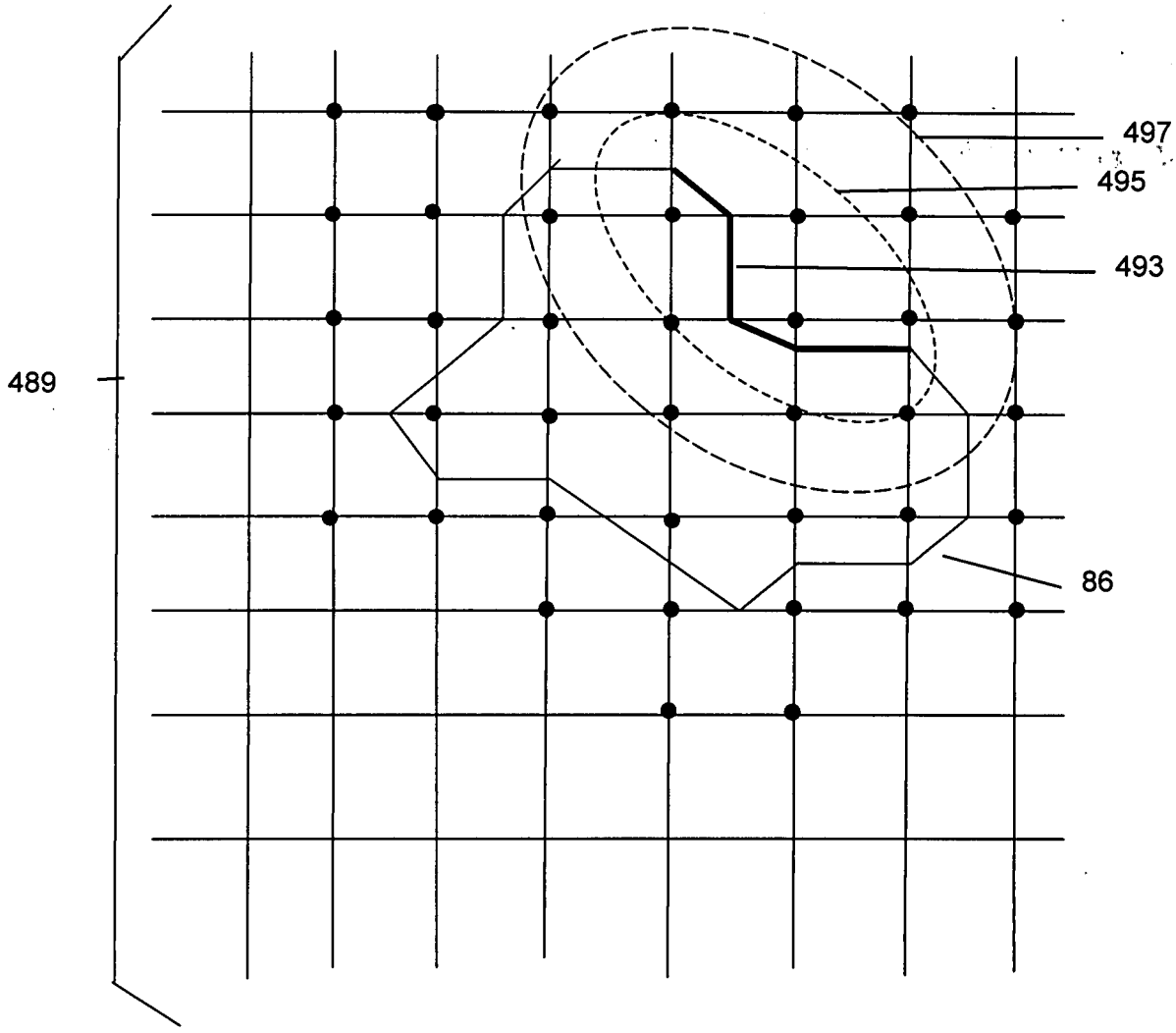

FIG. 24

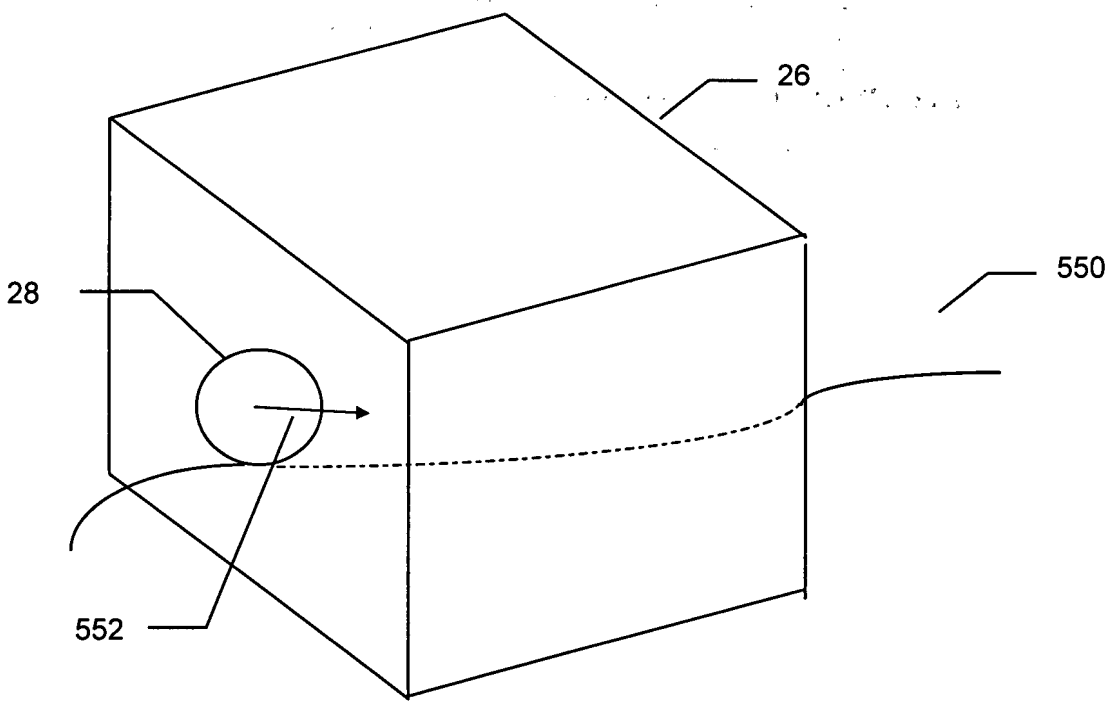

FIG. 25

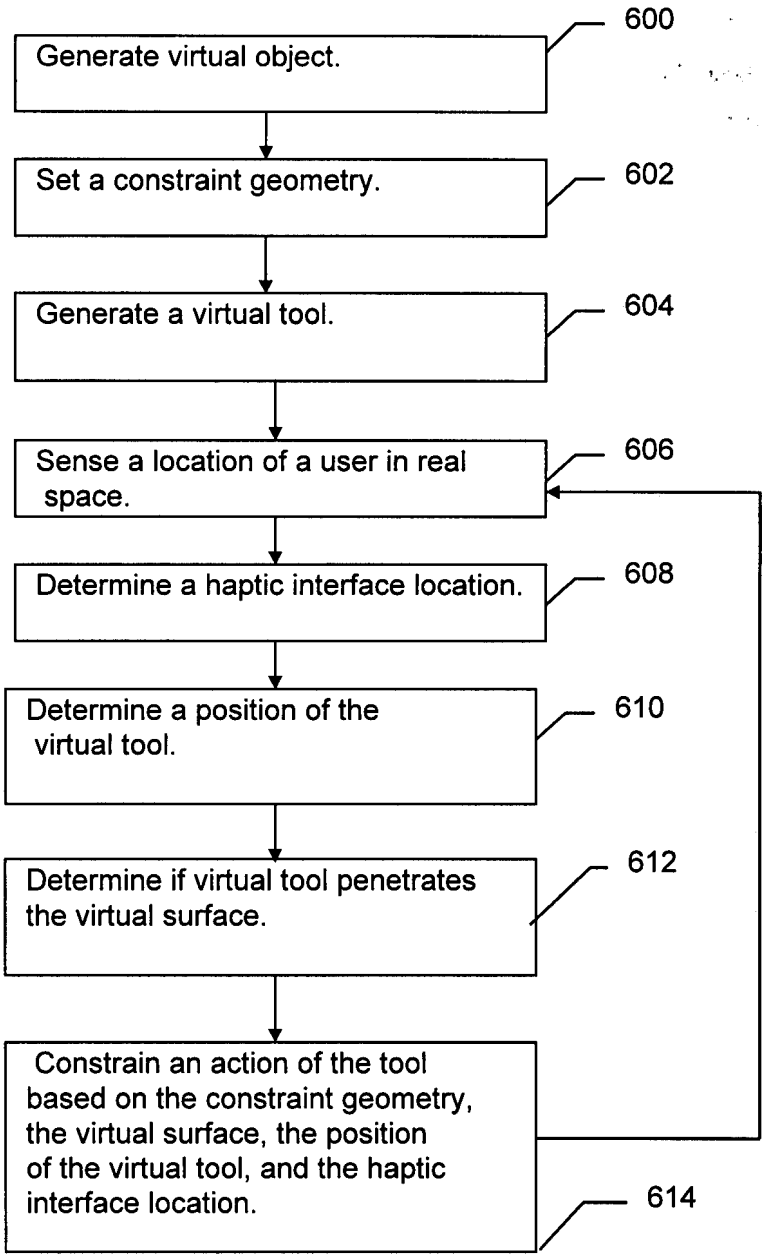
Generate virtual object.
600
Set a constraint geometry.
602
Generate a virtual tool.
604
Sense a location of a user in real space.
606
Determine a haptic interface location.
608
Determine a position of the virtual tool.
610
Determine if virtual tool penetrates the virtual surface.
612
Constrain an action of the tool based on the constraint geometry, the virtual surface, the position of the virtual tool, and the haptic interface location.
614

Fig. 26

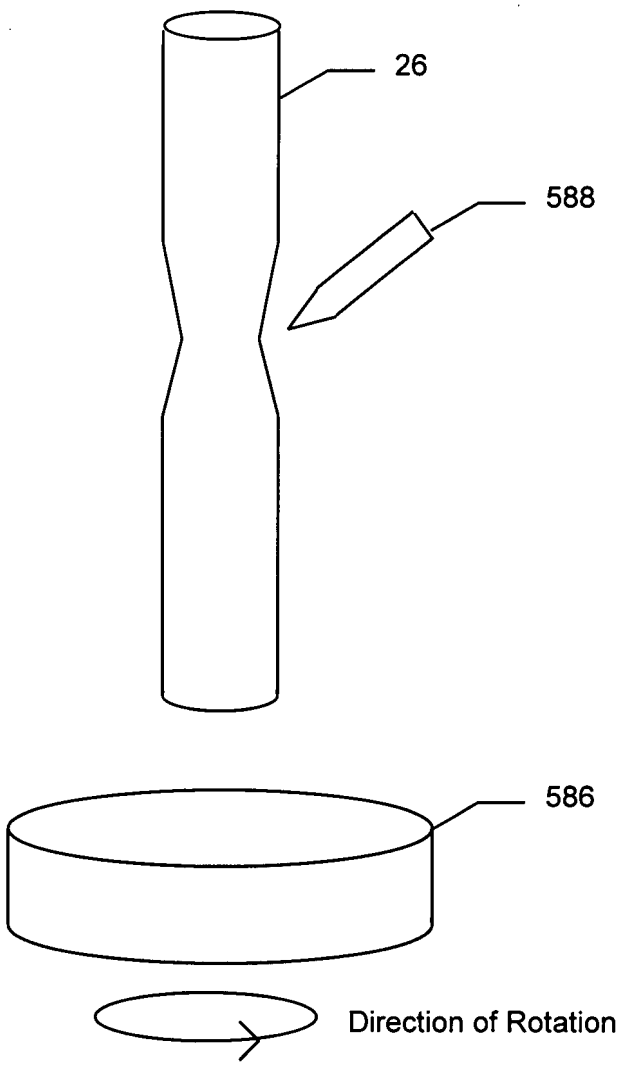

FIG. 27